7 PRINCIPLES and METHODS for TIME DOMAIN REFLECTOMETRY

7.1 Introduction

Time domain reflectometry (TDR) has become increasingly popular for the determination of soil water content. The technique depends on the measurement of the travel time of an electronic pulse through a wave guide (also called a probe) inserted in the soil. Topp et al. (1980) and other early researchers determined travel times in TDR probes by fitting tangent lines to wave form features by hand, either reading directly off the instrument screen or working with photographs of the screen. Since then, automatic wave form acquisition systems have been created that allow the collection of thousands of wave forms (Baker and Allmaras, 1990; Heimovaara and Bouten, 1990; Herklerath et al., 1991; Evett, 1993, 1994), thus necessitating the creation of computer programs for automatic interpretation of the wave form to find travel times. Several impediments have been encountered. Wave forms acquired in the field are often not as reproducible as those found in the laboratory. Wave form shape can change depending on probe construction or installation. Wave form shape varies quite dramatically with soil water content, bulk density, and salinity changes in the soil over time; with clay content changes between horizons and across the field; and with noise caused by various external factors or the data acquisition system itself. Since 1991 a set of algorithms was developed, field tested, and improved, leading to a reliable computer program for real time, unattended determination of travel times from TDR wave forms.

7.2 The TDR Method for Water Content Determination

The TDR method depends on the change in apparent permittivity of the soil which occurs when soil water content changes. The permittivity of the mineral matter in soil varies between 3 and 5. The permittivity of air, which may take up as much as 45% of the soil volume, is negligible. By contrast, the permittivity of water is about 80 (depending on temperature). As soil wets and dries its apparent permittivity, ϵ_a, changes accordingly, though not in a linear fashion. For four fine textured mineral soils, Topp et al. (1980) found that a single polynomial function described the relationship between ϵ_a and volumetric water content, θ:

$$\theta = (-530 + 292\,\epsilon_a - 5.5\,\epsilon_a^2 + 0.043\,\epsilon_a^3)/10^4 \qquad [1]$$

Commonly, implementation of the method employs a Tektronix TDR cable tester which was designed to find the location of faults in a cable. The cable tester consists of an electronic function generator which outputs a square wave signal with a very fast rise time (120 ps) and an oscilloscope timed to the square wave. The vertical axis of the oscilloscope screen has units of voltage while the horizontal axis has units of distance along the cable (or other wavequide). The units of the horizontal axis are set using the distance per division (DIST/DIV) setting. The horizontal axis is divided into ten divisions so that if DIST/DIV is set, for example to 0.2 m then the entire screen width represents 2 m.

The cable tester also has a setting for the relative propagation velocity, V_{pr}. This is the ratio of the velocity at which the signal propagates in a cable or other waveguide, v, to the velocity of light in a vacuum, c_o. The propagation velocity depends on the permittivity, ϵ, and the magnetic permeability, μ:

$$v = c_o(\epsilon\mu)^{-0.5} \qquad [2]$$

The permittivity of different insulations is different and the velocity of the signal changes accordingly. For example, for polyethylene insulation the velocity of the signal is about 0.66 times c_o so the relative propagation velocity is 0.66. The magnetic permeability is usually assumed to be unity.

It is important to understand that the oscilloscope measures time not distance. Therefore, in order to display distance on the horizontal axis of the screen the cable tester internally converts measured times to distances. The propagation velocity, v, is used to make the conversion. If the relative propagation velocity, V_{pr}, is set to 0.99 then the assumed propagation velocity is correspondingly:

$$v = 0.99\ c_o = 0.99 \times 0.299792 \times 10^9\ \text{m/s} \qquad [3]$$

To convert from time to distance, the cable tester uses this assumed value of v and the measured time in the following equation which relates the one-way distance, d, to the one-way travel time, t:

$$d = vt \qquad [4]$$

On the cable tester a 'Distance' knob allows the user to change the delay between signal propagation and oscilloscope scan. This delay amounts to the time that it takes the signal to travel a given distance down the cable and back to the oscilloscope pickup. Thus, the user can adjust the screen to show portions of the signal being reflected from different distances down the cable. Again, the cable tester uses the propagation velocity that we have chosen to convert the delay time to distance units so that the 'Distance' dial shows the correct distance. The distance will only be correct if we have chosen the correct relative propogation velocity. The signal trace on the oscilloscope screen will be flat except where discontinuities in the cable cause impedance changes and a partial reflection, or loss, of the signal. Reflections are caused by increases in impedance such as an open or broken conductor while signal loss is caused by decreases in impedance such as a short to ground.

For a cable the propagation velocity is known because the permittivity of the insulation is known. Therefore the time, required for the signal to travel to an impedance change and back again, can be used to calculate the distance to the impedance change. In the soil the apparent permittivity is unknown. However, we can construct probes (waveguides) which cause two impedance changes at a known distance from each other in the soil. Then we can use the cable tester to measure the time for the signal to travel from one impedance change to the next and use Eq. 2 to calculate the apparent permittivity which is the basic datum needed to calculate water content from Topp's equation. If t_t is the two-way travel time measured by the oscilloscope for the signal to travel from one impedance change to the other and back again, and L is the distance between the impedance changes then $v = 2L/t_t$. Substituting this into Eq 2, assuming $\mu = 1$, and rearranging we can calculate the apparent permittivity, ϵ_a:

$$\epsilon_a = [c_o t_t/(2L)]^2 \qquad [5]$$

Our problem is now reduced to finding the travel time, t_t, give the trace from the cable tester screen for a probe of known length, L. Note that we do not have to know the actual propogation velocity to get the correct value of t_t from the cable tester. We only have to know the propogation velocity factor that was set on the cable tester, when the wave form was measured, in order to convert the distance units reported by the cable tester back to time units by inverting Eq. 4.

A prototypical TDR signal from a 2 wire TDR probe constructed for water content measurements is shown in Figure 7-1. When the square wave signal reaches the point where the coaxial cable is connected to the rods a partial open circuit occurs because the outer braid is pulled away from the inner conductor. This partial open represents an increase in impedance which causes a reflection (increase in voltage) of the signal just before point t1 (Fig. 7-1). Immediately after passing through this partial open the signal leaves the insulating handle of the TDR probe and enters the rods buried in the soil. The moist soil causes a partial closed circuit (partial short circuit) compared to the handle and the signal voltage decreases (wave form height decends). The sudden increase and then decrease in reflected wave form height as the signal passes through the probe handle and into the soil causes the peak in wave form height at point t1. As the signal passes through the rods buried in the soil it typically encounters only small changes in permittivity and conducter configuration so no reflections are seen. This is shown in the low and flat part of the signal between points t1 and t2. When the signal reaches the ends of the rods in the soil it encounters an open circuit and is strongly reflected causing the increase in wave form height shown at point t2 in Figure 7-1.

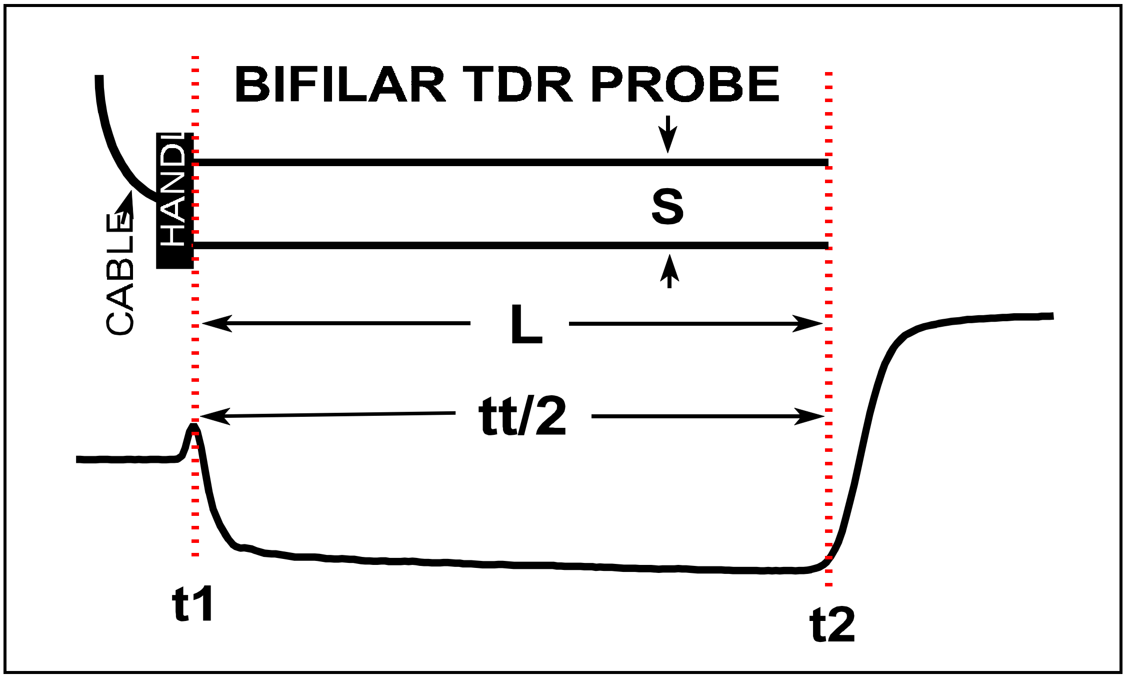

Figure 7-1. Relationship of TDR probe parts (top) to wave form features (bottom) for moist sand. For the wave form, the vertical axis has units of voltage and the horizontal axis units of time. The distance S is the rod spacing, L is the rod length, tt/2 is the one-way travel time, t1 is the time when the step pulse exits the probe handle to travel down the rods, and t2 is the time when the pulse reaches the ends of the rods and is reflected back.

If we measure the distance units along the horizontal axis between points t1 and t2 and convert the distance to time we can use this travel time in Eq. 5 to calculate the soil's apparent permittivity and use this value of ϵ_a to calculate the water content using Topp's or a similar calibration equation. For example, if we have set the DIST/DIV to 0.5 ft/division then, knowing that there are ten divisions across the screen we calculate that the horizontal axis represents 5 ft of distance from the leftmost division to the rightmost division. Furthermore, knowing the value of v that we have set in the cable tester we invert Eq. 4 to calculate the one-way travel time, t, represented by the horizontal axis:

$$t = d/v \qquad [6]$$

or, for a relative propagation velocity of 0.99:

$$t = [5 \text{ ft} \times 0.3048 \text{ m/ft}]/(0.99 \times 0.299792 \times 10^9 \text{ m/s})$$

$$= 5.13 \text{ ns} \qquad [7]$$

If we have measured the position of points t1 and t2 in units of screen divisions we need only divide t by 10 and multiply by the number of divisions to first, point t1, and then point t2 to find the travel times to these points. If we have measured the difference between points t1 and t2 in distance units we can enter the distance directly into Eq [6] (This is easy with the newer digital TDR cable testers). However, we note that the signal must travel twice the distance in order to go from point t1 to point t2 and back to point t1. The distance given on the horizontal axis of the screen is the one-way distance and so is the corresponding time. We must multiply by two to find the two-way travel time:

$$t_t = 2d/v \qquad [8]$$

Using Figure 7-1 as an example and counting screen divisions from the left hand side, we see that point t1 is at 1.1 screen divisions and point t2 is at 6.7 screen divisions, the difference between point t2 and point t1 being 5.6 screen divisions. Multiplying 5.6 by 0.513 ns per division gives 2.87 ns for the travel time from point t1 to point t2. Because the signal must travel from point t1 to point t2 and back again we multiply this travel time by 2 to get the full travel time t_t = 5.75 ns. Using Eq 5 and the probe length of 0.2 m we calculate ϵ_a = 18.6 and using Eq 1 we calculate θ = 0.33 which is a reasonable value for a well graded and packed saturated sand. Equivalently, we may multiply the difference in screen divisions between points t1 and t2 (5.6 divisions) by the distance per division which is [5 ft/(0.3048 m/ft)/10] = 0.1524 m. We calculate d = 0.853 m and using this value in Eq 8 we calculate a travel time of t_t = 5.75 ns which leads to a water content of 0.33 as before.

7.3 Description of wave form features as related to the TDR probe

The most basic TDR system consists of a pulse generator providing a step increase in voltage with a very fast rise time (typically 150 ps) and a fast oscilloscope that captures the wave form reflected from an attached cable or other waveguide (Topp et al. 1980). A TDR cable tester such as the Tektronix 1502 provides the pulse generator and oscilloscope in a tightly integrated unit. Note that although the cable tester gives distance as the units of the horizontal axis it really measures time. The cable tester may be adjusted to display on its screen any portion of the wave form including that part showing reflections from a probe installed in the soil.

Consider a TDR probe consisting of two stainless steel rods buried parallel to one another in a moist sand (non-saline) with the proximal ends soldered to coaxial cable (Fig. 7-1). The soldered connections are potted in epoxy. We will call the ensemble of epoxy potted connections the probe handle. The perpendicular distance between the rods is the separation distance, s, and the exposed length is L. Typically the coaxial cable would have a characteristic impedance of 50 ohms. A prototypical TDR wave form shows the reflections caused by the various parts of such a probe (Fig. 7-1). In particular, we are interested in the time necessary for the pulse to travel along the exposed length of the stainless steel rods, i.e. the one way travel time, tt/2.

The voltage level of the wave form at any time is representative of the impedance of the wave guide (cable or probe) at the corresponding physical location. Impedance has units of ohms but is a combination of resistance and inductance. Consider the coaxial cable leading to the probe. The cable features a very good insulator between the inner and outer conductors. For any length of the cable with uniform characteristics the voltage level of the line is unchanging except for a slight upward trend with increasing distance from the cable tester. Since the wave form level is representative of the impedance of the cable we expect the slight upward trend since the total resistance increases with cable length. If the characteristic impedance of the wave guide changes, this will cause partial reflections of the pulse. The sign of the reflections is determined by the sign of the change in impedance. If impedance increases the reflection is positive and the wave form level increases. If the impedance decreases the wave form level decreases corresponding to a negative reflection. The impedance, Z (ohms), of a transmission line (i.e. waveguide) is

$$Z = Z_0(\epsilon)^{-0.5} \qquad [9]$$

where Z_0 is the characteristic impedance of the line (when air fills the space between conductors) and ϵ is the permittivity of the (homogeneous) medium filling the space between conductors. For our parallel transmission line (the two rods in the soil) the characteristic impedance is a function of the wire diameter, d, and spacing, s (Williams, 1991):

$$Z_0 = 120 \ln\{2s/d + [(s/d)^2 - 1]^{0.5}\} \qquad [10]$$

or, if d<<s:

$$Z_0 = 120 \ln(2s/d) \qquad [11]$$

while for a coaxial transmission line the characteristic impedance is:

$$Z_0 = 60 \ln(D/d) \qquad [12]$$

where D and d are the diameters of the outer and inner conductors, respectively. From Eqs. 9 through 12 it is apparent that impedance, Z, increases as wire spacing increases and decreases as ϵ (water content) increases for any probe type.

The permittivity for a homogeneous material is defined for propogation of a sine wave as

$$\epsilon = \epsilon' - j(\epsilon'' + \sigma_{dc}/\omega\epsilon_0) \qquad [13]$$

where ϵ' and ϵ'' are the real and imaginary parts, respectively, σ_{dc} is the direct current conductivity, ω is the frequency of the wave, ϵ_0 is the permittivity of free space, and j is the square root of minus one.

Measurement of soil water content by TDR is based on the fact that the propagation velocity of an electromagnetic wave is given by (assuming $\mu = 1$)

$$v = c(\epsilon)^{-0.5} \qquad [14]$$

where c is the speed of light in free space. If $\epsilon' >> \epsilon''$ then

$$v = c(\epsilon')^{-0.5} \qquad [15]$$

and v is very nearly solely dependent on water content. If a Tektronix cable tester is used to measure the travel time, tt, this time is the two way travel time; and the velocity is v = 2L/tt. The value of permittivity calculated using the measured v and Eq. 14 or 15 includes both real and imaginary parts and is an apparent permittivity, ϵ_a. The volumetric water content can be related to ϵ_a as did Topp et al. (1980) using a polynomial regression, or directly to t_t in which case the relationship is closely linear.

The base line before the first peak in the wave form (Fig. 7-2) is the flat line to the left of the reflections caused by the probe. This preincident base line corresponds to the cable connecting the probe to the cable tester and the level of the base line corresponds to the impedance of the cable as described by Eqs. 9 and 12. At the connection between the cable and the proximal ends of the probe rods the cable is typically split (at t1.bis in Fig. 7-2) into two separate conductors with the outer braid of the coaxial cable twisted into a stranded wire that is connected to one stainless steel rod, and the inner conductor of the cable connected to the other rod. For trifilar probes, the outer braid is connected to the two outer rods and the inner conductor is connected to the middle rod.

Regardless of the probe type, at the connection point there is a widening of the separation between the conductors of the cable. According to Eqs. 9 and 10, the separation causes an increase in impedance between t1.bis and t1, causing a positive reflection and the first rising limb of the wave form (Fig. 7-2) (assuming the permittivity of the handle material is the same or lower than that of the insulation between the inner and outer conductors of the coaxial cable). Other features of the wave form can also be described by Eqs. 9 and 10. At the point where the rods exit the handle (t1 in Fig. 7-2) the permittivity increases (in moist soil) and impedance decreases, and a corresponding negative reflection occurs shown by the first descending limb in Fig. 7-2.

As the pulse travels along the rods it enters an environment of continuously decreasing complex impedance in moist soils due to the relatively low resistance of the soil to conduction of the signal voltage from one rod to

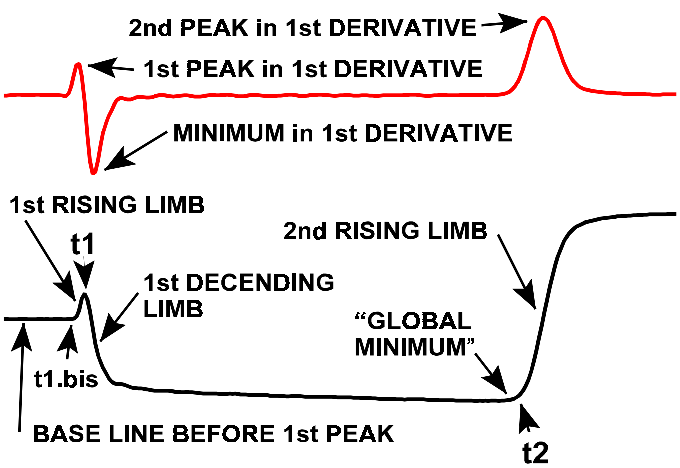

Figure 7-2. The TDR wave form (bottom) and its first derivative with respect to time(top), with features labeled.

the other. The total resistance decreases with probe length so the impedance decreases as well. This causes negative reflections at all points along the rods. Since the resistance is continuously (and usually smoothly) decreasing with rod length the reflections are not sudden as they are at the connection of the cable to the rods. Thus, the wave form shows a continuous decline as distance from the handle increases.

The distal ends of the rods represent an open circuit with corresponding high impedance since the wave guide ends. This causes a large positive reflection and a jump in the level of the wave form - the second rising limb (Fig. 7-2).

7.4 Visual Wave Form Interpretation and Early Computer Programs

Topp et al. (1982) described a method of interpreting wave forms captured on paper using a chart recorder or by photographing an oscilloscope screen. This analysis consisted of two graphical algorithms. Algorithm 1 consisted of drawing a horizontal line across the top of the first peak, and drawing a line tangent to the descending limb of the first peak (Fig. 7-2). The intersection of these lines defined t1. Algorithm 2 consisted of drawing a horizontal line tangent to the base line between the first peak and second inflection, and drawing a line tangent to the second inflection. The intersection of the latter two lines defined t2. The travel time of the pulse in the part of the wave guide that was buried in the soil was tt=t2-t1. Peaks and inflections were identified by eye and no computer code or algorithms were presented.

Later, Baker and Allmaras (1990) discussed a computer program for interpretation of wave forms following the ideas of Topp et al. (1982). The program, which was not published, included the following steps applied to a wave form consisting of 200 data points (Fig. 7-3):

1) Smooth and differentiate the data (Savitsky and Golay, 1964).
2) Use a loop to search the wave form data for the global minimum, VMIN, and associated time, t2.1.
3) Find the local maximum, V1MAX, and associated time, t1p, in the data between the first point and t2.1. This is the time, t1p, of the first peak.
4) Find the most negative derivative, DMIN, the corresponding time, tDMIN and wave form value, VtDMIN, in a region of 25 points following t1p. The slope of the first descending limb is DMIN.
5) Define a line with intercept V1MAX and slope of zero that is horizontal and tangent to the first peak. Define a second line with slope DMIN and intercept such that it passes through VtDMIN at tDMIN. Solve the two lines for their intersection point and associated time, t1, that corresponds to the point where the rods exit the handle.

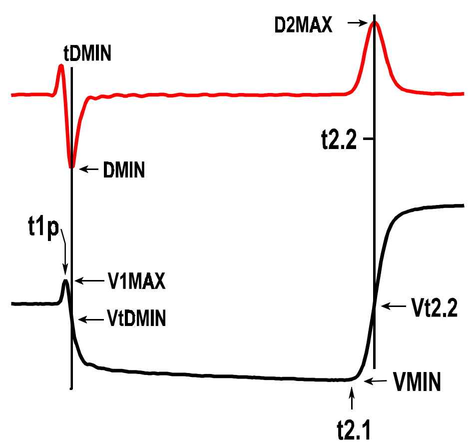

Figure 7-3. The TDR wave form (bottom) and its first derivative (top) with features identified by Baker and Allmaras (1990) (our nomenclature).

6) Find the maximum derivative, D2MAX, in a region of 25 points following VMIN, and associated time t2.2 and wave form value Vt2.2.
7) Define a line tangent to the second inflection with slope D2MAX and passing through Vt2.2 at t2.2. Define a horizontal line tangent to VMIN. Solve for the intersection of these lines to find t2, the time corresponding to the ends of the rods.

The travel time of the pulse through the exposed length of the rods was t_t = t2-t1. While these algorithms worked well for relatively moist soils there were problems with the absence of DMIN and absence or movement of VMIN and associated times in wave forms for dry, low bulk density soils (see Section 7.5.1).

Heimovaara and Bouten (1990) described a computer program that involved fitting lines to the second inflection and to the base line between t1 and t2. The regions of data points to which these lines were fit were determined empirically for a given probe. Also, they recognized that the wave form might not always descend at t1 and so introduced the concept of fitting lines to the rising limb of the first inflection and to the base line before the first inflection, and using the intersection of these lines to define a time, t1.bis, corresponding to the point of separation of the cable conductors. A correction time was added to t1.bis to get t1. This correction time was determined by performing a single measurement in air before probe installation.

The methods of Topp et al. (1982), Baker and Allmaras (1990), and Heimovaara and Bouten (1990) were found not to work for all Pullman clay loam soil conditions encountered at Bushland, Texas and in other soils in the early 1990s. Specific problems encountered and methods of dealing with them will be discussed in the following sections.

7.5 Factors Influencing Wave Form Shape

Many conditions may alter the wave form from the classical forms displayed in Figures 7-1, -2, and -3. It is perhaps an accident of location, climate, and soil type that many of the early computer algorithms emphasized finding the minimum, VMIN, and its time, t2.1; the second maximum in the first derivative, D2MAX, and its time, t2.2; and the minimum of the first derivative, DMIN, and its time, tDMIN (see Fig. 7-3). In humid environments where soils are seldom dry, and are well leached so that bulk electrical conductivity is low, these features are found in almost all wave forms and can be reliably used as keys for computer analysis. However, in dry soils DMIN and the descending limb of the first peak may disappear. Also in dry soils, the position of VMIN may change dramatically, moving from the right side to the left side of the wave form. In soils with high bulk electrical conductivity the wave form may rise only slowly at the point corresponding to the ends of the rods; making the value of D2MAX so low as to be lost in the noise level of the first derivative. These and other factors influencing wave form shape are discussed here. Later, a suite of algorithms for interpreting wave forms despite these changes in shape will be presented.

7.5.1 Influence of Dry Soil on Wave Form Shape

As the soil drys, the first descending limb (Fig. 7-2) becomes less steep. Since dry soil has about the same permittivity as the plastic materials used in most probe handles there may be little or no impedance change between the wave guide in the handle and in the soil. Indeed, if the soil is both dry and of low bulk density the impedance of the wave guide may actually increase in the soil compared to the handle. Both conditions cause the first descending limb to be absent (Fig. 7-4) and render ineffective both algorithm 1 of Topp et al. (1982) and the corresponding methods of Baker and Allmaras (1990). Dry soils of low bulk density are usually found close to the surface. Since this is where the TDR method enjoys its greatest advantage compared to its nearest competitor, neutron scattering, it is imperative that the method be usable in such soils. For dry soil the second inflection, caused by the distal ends of the rods, is invariably steep and high, making it easy to find by searching for D2MAX. However, at the same time the global minimum may not occur after t1 or the position of the local minimum may shift from just before the second inflection to a point just after the first peak, or to any intermediate position. This causes variations in the intersection of the two lines (horizontal tangent to global minimum and tangent to second inflection) that have no relation to the travel time, t_t.

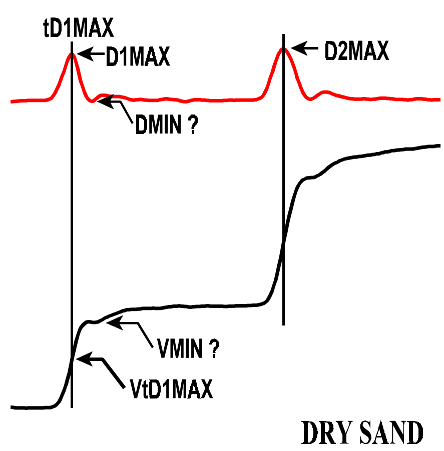

Figure 7-4. Influence of dry soil on wave form shape illustrating difficulty of finding DMIN and VMIN.

Another phenomenon sometimes found in low bulk density soils is the double peak. This may be due to compression of a thin layer of soil next to the handle as the probe was inserted into the soil at installation time. This higher bulk density soil will exhibit a lower impedance due to lower porosity (air has a permittivity of 1) and will cause the dip in the wave form after the handle. As the pulse enters less compressed soil it encounters a higher impedance and the reflected wave form rises, only to lower again as the pulse travels further down the rods (due to the impedance decline associated with the lowering of total resistance with rod length). It is important to have an algorithm to discriminate between these peaks.

7.5.2 Influence of Probe Design on Wave Form Shape

The height of the first peak increases with the separation distance of the rods because the impedance at this point in the wave guide increases with the separation distance (Eq. 10; Fig. 7-5). The impedance and peak height are inversely proportional to the diameter of the rods. The height is also influenced by the permittivity of the material separating the proximal ends of the probes (Eq. 9). For a handle made of epoxy (ϵ_a approx. 3), rod diameter of 3.2 mm and spacing of 30 mm the characteristic impedance increases from 50 ohms in the cable to approx. 90 ohms in the part of the stainless steel wave guide embedded in the handle (Fig. 7-5). The pulse travel time between t1.bis and t1 increases with the permittivity of the material between the point of splitting the antenna cable and the connections to the rods. It also increases with the separation distance of the rods. Finally, this travel time increases with the distance between the split in the cable and the point of connection to the rods.

Consider an early type of TDR probe consisting of two stainless steel rods buried parallel to one another in the soil with the proximal ends connected to bifilar antenna cable. Connections were sometimes made using alligator clips, sometimes soldered, and sometimes made by clamping the wire to the rod with a screw. The perpendicular

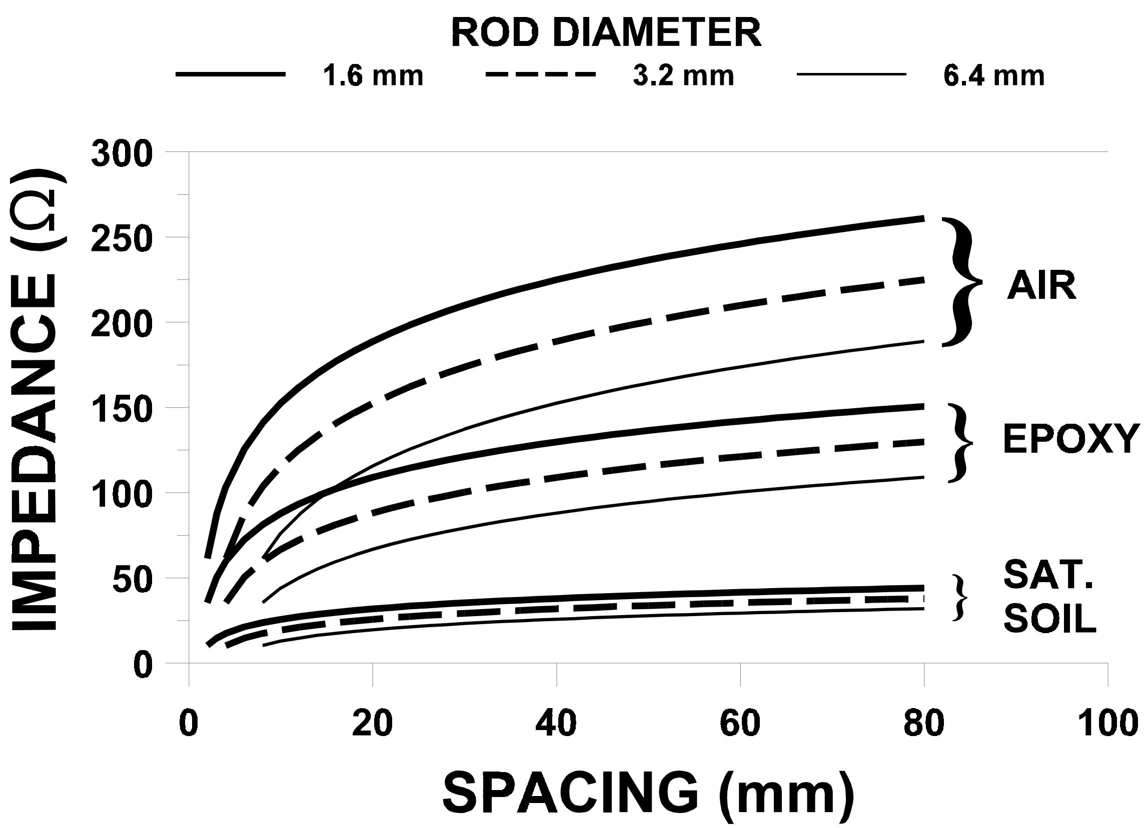

Figure 7-5. Influence of rod spacing, rod diameter, and permittivity of the medium on impedance of the waveguide according to Eqs. 9 and 10. Permittivities are: AIR, close to unity; EPOXY, close to 3; and SATurated SOIL, approx. 35.

distance between the rods was the separation distance. Typically the antenna cable would have a characteristic impedance of 300 ohms. In order to match impedances (thus lowering signal loss and distortion) between the antenna cable and the 50 ohm wave guide of the cable tester a balun (transformer) would usually be used to connect the antenna cable to the cable tester. In the case of our probe made with antenna cable and two rods, the connections are separated by the soil between the distal ends of the rods. In this case the height of the peak is influenced not only by the separation distance but by the water content of the intervening soil (assuming the probe is buried). For dry soil the impedance may be nearly the same as for epoxy but for wet soil the value of ϵ_a may approach 35 and the impedance may be 30 ohms or lower (Fig. 7-5).

Using our probe made with antenna cable and two rods we can see several reasons why the height of the first peak and the time between t1.bis and t1 might not be reproducible between probes in the field. The length of cable split may vary, the separation distance at the proximal rod ends may vary (over time even if controlled at installation), and the permittivity of the porous medium separating the two wires of the wave guide may vary in time and space between the cable split and the point of connection to the rods. If the rods are installed vertically and the point of connection is at the soil surface the split cable may be separated by air, whereas if the probe is installed deeper in the soil the split cable will be separated (along at least some of its length) by soil that varies in permittivity as it wets and drys.

If we have a reliable algorithm for finding t1 we need not worry about the time between t1.bis and t1. However, as we have seen, there are soil conditions that make finding t1 alone practically impossible. Also, the varying permittivity of the material separating the rods makes the height of the first peak variable (the first rising limb may cease to exist under some conditions), further complicating the search for t1. If t1 is difficult to find we may search for an algorithm that finds t1.bis reliably. But, since the travel time we ultimately need is tt=t2-t1 not t2-t1.bis, we would need to have a consistent time (t1 - t1.bis) in order to use t1.bis to find tt. With our probe made of antenna cable and two rods it is virtually impossible to guarantee consistent conditions that would allow reliable determination of either t1 or t1.bis, or that would quarantee that t1=t1.bis+t_C where t_C is a constant.

For these reasons the TDR probes commercially available today are invariably made with the split in the cable (usually coaxial cable) and the connections to the rods fixed in some sort of rigid configuration, usually called the handle; and enclosed in a material of consistent and constant permittivity. The handle may be made of epoxy resin, delrin, polymethyl methacrylate (acrylic), RTV silicone or some other plastic and may contain metal for shielding or connection of rods. These handles share the properties of a fixed separation distance, fixed permittivity of the material separating the conductors of the wave guide in the handle (with some minor temperature variations), fixed distance between the cable split and the point of connection to the rods, and fixed distance between the point of connection at the proximal ends of the rods and the point at which the rods exit the handle and enter the soil. Such handles provide optimal conditions for reliable algorithms determining t1.bis and t1, and the rest of this discussion will assume such a handle.

It has been argued (Spaans and Baker, 1993), that in order to match impedances (thus lowering signal loss and distortion) between the coaxial cable and the two rods in a bifilar probe, a balun should be used at the point of connection. Also, the balun should serve to convert the unbalanced signal in the coaxial cable (where the inner conductor carries the wave form and the outer conductor remains at virtual ground) to a balanced signal in the two rods (where both conductors carry the wave form. The argument states that, absent a balun, the unbalanced signal will tend to balance as it travels down the rods, eventually becoming closely balanced at some point along the rods. But, between the handle and that point the signal reflections will be distorted due to the partial imbalance. If the rods are very short the distorted part of the wave form may interfere with the second inflection. The trifilar probe responds to this concern by providing a waveguide that is geometrically more similar to a coaxial waveguide (Zegelin et al., 1989). Measurements by Zegelin et al. (1989) show only minor differences in wave form shape between trifilar and coaxial waveguides.

7.5.3 Influence of Bulk Electrical Conductivity on Wave Form Shape

As the bulk electrical conductivity (BEC) of the soil increases the impedance of the wave guide in the soil decreases due to the lowering of the resistance component of impedance. In addition there is a lowering of signal voltage along the length of the rods due to conduction through the soil. This causes the wave form level after the first peak to decline relative to that for a soil of lower BEC. It also lowers the slope, D2MAX, of the second rising limb (Hook and Livingston, 1995) and the final height to which the wave form rises after the second inflection. This latter fact has been used successfully to find the BEC of soils (e.g. Dalton et al., 1984; Topp et al., 1988; Wraith, 1993).

However, these effects can make it difficult to reliably find the second rising limb by searching for D2MAX. Smoothing of the wave form and its first derivative can make the determination of D2MAX more reliable by reducing the relative height of peaks in the first derivative that are caused by random noise in the wave form. However, in case of a very weak second rising limb the peak in the first derivative can be so spread out that the apparent position of the second rising limb, deduced from the position of D2MAX, is not consistent. Fortunately, in these cases the high BEC guarantees that the wave form will slope downward between t1 and t2, in turn guaranteeing that the position of VMIN is always just before the second rising limb. Thus, in this situation, VMIN can be used reliably as the key to an algorithm used to find t2 described below.

Unfortunately, increased soil salinity is only one source of increase in BEC. Another source of BEC is the conductivity arising from certain clays, especially clays with high CEC. These are often expanding lattice clays containing cations entrapped between clay layers. When such soils are dry they exhibit low BEC, probably due to the contracted nature of the clay micelles and discontinuous water films on soil particles and the resulting low mobility of cations. As these soils wet their BEC increases as shown in Fig. 7-6 for an expansive Pullman clay loam with mixed minerology at Bushland, TX. The effects are apparent as a lowering of the second inflection and final wave form height as these soils wet. Although the problems posed by this phenomenon vis-a-vis the finding of t2 can usually be solved, the implications for relating TDR wave forms to soil salinity cannot be ignored.

Furthermore, this phenomenon has implications for the application of frequency domain (FD) probes to water content determination in these soils, similar to the implications and reported problems related to salinity effects on water content determination by FD probes. A frequency domain probe relies upon the change in frequency of an oscillator circuit caused by the change in permittivity of the soil around the probe. For the oscillator to change states the reflected voltage must reach the set point voltage of the oscillator at which time the oscillator changes states and drives the wave guide to the opposite polarity. The time it takes for the reflected voltage to reach the set point is determined not only by the travel time to t2 but by the additional time between t2 and the time at which the second rising limb rises to the set point. Thus, the frequency of oscillation is dependent not only on t2 or t2-t1 but on the BEC of the medium. Since the BEC may be changed by salinity changes, clay content changes and/or water content changes in a clayey or saline soil it is obvious that calibration of an FD probe for routine field use, where these factors may change in time and space, is problematic. Not all clay soils show increases in BEC with water content as illustrated in Fig. 7-7 for a Cecil clay of kaolinitic minerology from Watkinsville, GA.

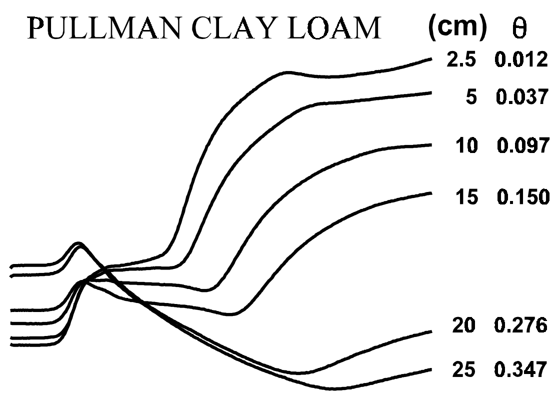

Figure 7-6. Effect of soil water content (θ, $m^3 m^{-3}$) on the bulk electrical conductivity of a non-saline clay loam at several depths (cm) in the A horizon (2.5 to 15 cm) and B horizon (20 and 25 cm).

7.5.4 Influence of Equipment and Acquisition Method on Wave Form Shape

There are myriad ways to generate the TDR pulse and capture the reflected wave form. Some of the first systems used a separate pulse generator and oscilloscope and captured the wave form by photographing the oscilloscope screen. The Tektronix 1502, 1502B and 1502C TDR cable testers have also been used very widely and successfully. This discussion is limited to Tektronix cable testers although some of the discussion will apply to other instruments. The model 1502 is an analog output device that outputs a voltage level to drive the pen on a chart recorder when a toggle switch is pushed. The X-output is a ramping voltage to drive the x-axis movement of the pen at a constant speed across the paper. The Y-output is a voltage varying with the level of the wave form at an ordinate on the wave form corresponding to the level of the ramping X-output. The instrument takes 20 s to output a signal in this fashion. Baker and Allmaras (1990), Herkelrath et al. (1991), Evett (1993, 1994) and others described systems for capturing the Y-output signal unattended and in electronic digital form by using a data logger or computer to toggle the output via a relay and digitizing the Y-output voltage, storing the set of values in memory. The digital models 1502B and 1502C simplified the process of wave form capture by digitizing the wave form internally and providing a digital connection to a computer (usually via RS-232 serial port).

There are trade offs between the digital and analog cable testers. The pulse of the analog model 1502 has a 120 ps rise time, somewhat faster than the 150 ps rise time for the digital models. The Y-output of the 1502 can be digitized to almost any precision desired and many points across the wave form can be captured. For instance it is relatively easy to digitize to 12 bits resolution and capture 400 points per wave form using inexpensive equipment. The number of points captured has some implications for the reliability of computer algorithms. The digital cable tester provides 251 points across the wave form and is not adjustable in this respect. In some situations the first peak in the wave form may be so very sharp that it is less than one point wide. In such a case the peak may not appear on every wave form. Toggling the 1502 to output a wave form and digitizing the Y-output is prone to some errors in that the timing of wave form output and data acquisition may be difficult to synchronize. This can result in digital wave form data that are good in the middle but have sharp drops or rises at the ends that are artifacts of the data acquisition process, and not related to the wave guide and soil. A computer program must discriminate against these artifacts.

With any form of digitization there is the certainty of some noise in the digitized wave form plus the possibility of noise in the signal arising from outside sources. Smoothing of the wave form can reduce the influence of noise on the effectiveness of algorithms for finding t1 and t2 by making clearer the times tD1MAX and t2.2 of the peaks in the first derivative. But excessive smoothing can result in errors due to loss of peaks in either the wave form or its first derivative. Also, excessive smoothing can change the slopes of the rising and descending limbs of the wave form to which tangent lines are fit. This in turn can change the point of intersection of tangent lines and the value of t1 or t2 derived from these intersections. The models 1502B and 1502C offer smoothing of the wave form by averaging of successive captured wave forms. While effective this may take more time than computer algorithms for smoothing such as those employed by Baker and Allmaras (1990).

7.5.5 Influence of Cable Length on Wave Form Shape

As the pulse moves down the cable to the probe its higher frequency components are selectively attenuated. The cable acts as a low pass filter. This means that the longer the cable, the slower the rise time of the pulse at the probe, and the less steep the rising and descending limbs of the inflections caused by probe handle and end of rods, i.e. transition time increases (Hook et al., 1992; Hook and Livingston, 1995). If the wave form is correctly interpreted then the travel time, t_t, should be constant despite cable length. However, if the probe is short enough, the descending limb of the first peak will intersect the rising limb of the second inflection causing the travel time to be incorrect. The longer the cable, the lower the slope of the descending limb and the longer the probe must be to avoid this problem. However, longer probes cause increased attenuation of the step pulse due to DC conduction through the soil between the rods and due to the lossy nature of soils. In some soils the increased attenuation causes the reflection of the step pulse at time t2 to be lost. Since the slope of the descending limb also decreases with increasing BEC of the soil, a probe length appropriate for a given cable length is difficult to predict. Another problem associated with long cable lengths is the loss of the first peak altogether.

7.6 Algorithms for Graphical Interpretation of Wave Forms

The preceeding discussion shows that computer based interpretation of TDR wave forms requires algorithms that include decision making ability, encapsulating as far as possible the human ability to recognize the inflections of the wave form reliably despite severe changes in shape; as well as the human ability to disregard noise. Such algorithms are described below in the order in which they are employed in the TACQ.EXE program.

7.6.1 Positioning of the Wave Form on the Screen

We are aware of no reports that describe a method for positioning the wave form on the cable tester screen that allows for reproducible and consistent computerized finding of t_t. Yet positioning has a direct affect on whether enough data are present to reliably fit lines to various portions of the wave form. Consider a wave form similar to that in Figs. 7-1 to 7-3 but occupying only a portion of the screen. Since the data are digital representations of an analog phenomenon there are only a fixed number of data pairs of voltage and time representing a screen of data. For instance for the Tektronix model 1502B/C cable testers there are 251 data pairs. For Fig. 7-2 there were only 4 data pairs in the first rising limb, 12 data pairs in the first descending limb, and about 25 data pairs in the second rising limb. For Fig. 7-4 there were 18 data pairs in the first rising limb, only 3 data pairs in the first descending limb, and 24 data pairs in the second rising limb. If the wave forms were compressed horizontally even by 50% it would be difficult to find enough data points to fit tangent lines to key parts of the wave forms. Thus it is best to have the wave form occupy as much of the screen as possible. This is easily accomplished using the distance per division, DIST/DIV, and relative velocity of propogation, V_{pr}, settings of the cable tester. However, the width of the wave form increases with soil water content, and unless the cable tester is set when the water content is at saturation the wave form may widen enough with increasing water content that the second rising limb can no longer be seen on the screen. Figure 7-6 illustrates this. If the wave form width had been set to occupy the full screen for dry soil (2.5 cm depth, θ = 0.012), the wave form for wet soil (25 cm, θ = 0.347) would be too wide for the second rising limb to appear on the screen.

Fortunately, if we have a good idea of what the saturated water content would be for a given soil, we can compute the desired screen width in ns as follows. First compute the apparent permittivity from Eq. 16 (Topp et al., 1980):

$$\epsilon_a = 3.03 + 9.3\theta_s + 146\theta_s^2 - 76.7\theta_s^3 \qquad [16]$$

where θ_s is the saturated water content. The saturated water content can be estimated from the soil dry bulk density, ρ_b. Simply calculate the total soil porosity, $f = 1 - \rho_b/\rho_p$, where ρ_p is the particle density (assumed equal to 2.65); and assume that all air is displaced when the soil is saturated so that $\theta_s = f$. Calculate the velocity of propogation using Eq. 2. Then calculate the travel time over the length of the probe by inverting Eq. 4. Adding additional time for the base line before the first peak and for the second rising limb after t2 we have the time that we wish to have represented by the full screen width. Then we have only to find a combination of distance per division (DIST/DIV) and relative propagation velocity (V_{pr}) settings that results in a full scale horizontal axis at least equal to this time. Experience shows that it is best to have at least one tenth of the screen width (one division) between the left had side of the screen and the first peak in order to reliably fit the base line. Also it is best to have at least 0.2 of the screen width between t2 and the right hand side of the screen to reliably fit the tangent to the second rising limb. A computer algorithm for finding appropriate combinations of DIST/DIV and V_{pr}, given the soil's saturated water content and the probe length, is given in Appendix 7-A. Example results for several probe lengths and saturated water contents are given in Table 7-1. These are for the Tektronix 1502B or 1502C cable testers which allow variation of Vp settings in hundreths.

Table 7-1. Optimum relative propagation velocity (V_{pr}) and distance per division (Dist/Div) settings and resulting screen widths in ns for several combinations of probe length and saturated water content. Settings give screen widths within 2% of those calculated using the assumptions in the preceeding paragraph.

	$\theta_s = 0.5$			$\theta_s = 0.4$			$\theta_s = 0.3$		
Probe Length (m)	V_{pr}	Dist/Div (m)	screen width (ns)	V_{pr}	Dist/Div (m)	screen width (ns)	V_{pr}	Dist/Div (m)	screen width (ns)
0.05	0.59	0.025	1.40	0.69	0.025	1.20	0.85	0.025	0.98
0.10	0.59	0.05	2.80	0.69	0.05	2.39	0.42	0.025	1.96
0.15	0.39	0.05	4.20	0.46	0.05	3.59	0.56	0.05	2.94
0.20	0.59	0.10	5.61	0.69	0.10	4.78	0.42	0.05	3.92
0.30	0.39	0.10	8.41	0.46	0.10	7.18	0.56	0.10	5.87

For the older Tektronix model 1502 cable tester, the V_{pr} setting has much less flexibility. There are three buttons for V_{pr}. Pressing Solid PTFE gives a V_{pr} of 0.70; pressing Solid POLY gives a V_{pr} of 0.66; and pressing OTHER allows the V_{pr} to be adjusted from 0.55 to 0.99 by turning the VAR screw. When all three buttons are out the V_{pr} is 0.99; or, when the VAR button is pressed in and the VAR screw is turned all the way clockwise, the V_{pr} is 0.99. Unfortunately, there is no simple way to know the exact V_{pr} value that is set with the VAR screw, so the user is left with just three usable V_{pr} settings, 0.66, 0.70, and 0.99. If the Tektronix 1502 is selected in Software Setup in TACQ then pressing D for defaults will, in addition to allowing the user to set the V_{pr} and Dist/Div settings, give two recommendations for Dist/Div (using the V_{pr} value chosen by the user). The first recommendation will show a negative percent error, and the second will show a positive percent error. These are the percentages difference from the optimum screen width in ns. If the negative percent error is small, then the user may be able to use the corresponding Dist/Div recommendation. Otherwise, the user should use the Dist/Div recommendation that gives a positive percent error. This will result in a screen width in ns that is wider than absolutely necessary, but that will ensure that the second rising limb of the wave form is not lost off the right side of the screen when the soil becomes saturated. The user should use Vp values of 0.66, 0.70, and 0.99 and see which gives the smallest percent error. Tables 7-2 and 7-3 give some possible combinations of probe length and Dist/Div and associated errors as a percentage of the optimum screen width in ns for V_{pr} values of 0.99 and 0.70, respectively.

Table 7-2. Distance per division (Dist/Div) settings, and associated errors compared with optimum screen width, for V_{pr} of 0.99 and for a range of saturated water contents and probe lengths. For a cable tester set for units of feet.

	θ_s = 0.5		θ_s = 0.4		θ_s = 0.3	
Probe Length (m)	Dist/Div (ft)	Percent Error	Dist/Div (ft)	Percent Error	Dist/Div (ft)	Percent Error
0.05	0.1	-27	0.1	-14	---	---
	0.2	47	0.2	72	0.1	5
0.10	0.2	-27	0.2	-14	0.1	-48
	0.5	83	0.5	115	0.2	5
0.15	0.2	-51	0.2	-43	0.2	-30
	0.5	22	0.5	43	0.5	75
0.20	0.5	-8	0.2	-57	0.2	-48
	1.0	83	0.5	7	0.5	31
0.30	0.5	-39	0.5	-28	0.5	-13
	1.0	22	1.0	43	1.0	75

It is obvious that for some combinations of probe length and saturated water content there is no combination of Dist/Div, and the Vp settings possible with the push buttons on the Tektronix 1502 cable tester, that comes close to providing an optimum screen width. This doesn't necessarily mean that good data can't be obtained, but it does mean that the user may want to chose probe lengths that lend themselves more easily to optimization of this sort.

Table 7-3. Distance per division (Dist/Div) settings, and associated errors compared with optimum screen width, for V_{pr} of 0.70 and for a range of saturated water contents and probe lengths. For a cable tester set for units of feet.

	θ_s = 0.5		θ_s = 0.4		θ_s = 0.3	
Probe Length (m)	Dist/Div (ft)	Percent Error	Dist/Div (ft)	Percent Error	Dist/Div (ft)	Percent Error
0.05	---	---	---	---	---	---
	0.1	4	0.1	21	0.1	48
0.10	0.1	-48	0.1	-39	0.1	-26
	0.2	4	0.2	21	0.2	48
0.15	0.2	-31	0.2	-19	0.2	-1
	0.5	73	0.5	102	0.5	147
0.20	0.2	-48	0.2	-39	0.2	-26
	0.5	30	0.5	52	0.5	85
0.30	0.5	-14	0.2	-60	0.2	-51
	1.0	73	0.5	1	0.5	24

7.6.2 Wave Form Smoothing

Wave forms are smoothed using the Savitsky-Golay procedure (Gorry, 1990). The user may choose any degree of smoothing from none to a 21 point smooth. Only odd numbers of points are allowed to provide a symmetrical smooth. Derivative smoothing may vary from none to a 19 point smooth. Derivative smoothing must be over a number of points at least two lower than the number chosen for wave form smoothing. The user should speficy only enough smoothing to reduce extraneous peaks in the first derivative. Excessive smoothing can cause errors, most particularly loss of sharp wave form features such as the first peak.

7.6.3 Circumscribing Wave Form Interpretation

In order to avoid dealing with sudden drops or rises in level that may occur at the beginning or end of the wave form (usually only seen with the 1502 cable tester) the user may set any number of points not to be used in wave form interpretation at either end of the wave form. Vertical lines on the screen show the parts of the wave form thus excluded. The number of points for either end may be set by entering a number or by moving the lines interactively using the cursor keys. Also, the user may define a limit excluding data in the right hand side of the wave form from being used to find the first peaks in the wave form and first derivative. This excludes the second peak in the first derivative from consideration for finding time 1and eliminates confusion between the first and second rising limbs. Correspondingly, the user may exclude a portion of the left hand side of the wave form from consideration when determining the location of the second rising limb. Again, these limits may be set by entering a number or by using the cursor keys to move the vertical lines that represent the limits on the computer screen.

<u>User Set Limits on Data Searched for Wave Form Features:</u>

StartPt	Time before which to exclude data from examination.
EndPt	Time after which to exclude data from examination.
D2Lim	Time at which to begin search for second maximum in the first derivative. Search ends at EndPt.
D1Lim	The data between StartPt and D1Lim are searched for the first peak in the first derivative, D1MAX.
SafetyLim	If t1 is less than this time then zeros are written to the output.
t1Swath	Number of data points after tD1MAX to use when searching for V1MAX.

7.6.4 Choosing Wave Form Interpretation Methods:

For finding the center of the second rising limb (t2.2) the user may choose to use only a global minimum method (i.e. find VMIN and t2.1), only a method that finds D2MAX and associated time t2.2, or an automatic method that uses the global minimum method if the value of D2MAX is below a user set threshold, D2Thresh, and that uses the time of D2MAX otherwise. The global minimum method for t2 is similar to that of Baker and Allmaras (1990) except that the search for VMIN is conducted in the data between t1p and EndPt rather than over all the data. Regardless of the method for finding t2.2 the line tangent to the second rising limb is found by linear regression on a swath of points around t2.2 (user chosen swath width).

The user may choose how to fit the "horizontal" intersecting line that partially defines t2. The line is either a horizontal line passing through the wave form at t2.1 or a line fit by regression to a swath of points just prior to t2.1 (user chosen swath width). If the horizontal tangent method is chosen the program will examine the slope of a fitted line and if the slope is positive the program will use the fitted line rather than the horizontal tangent. This avoids improper interpretation of wave forms from dry soils for which VMIN may be located closer to t1 than t2.

For finding t1 the user may choose to use a method (M1), similar to that of Baker and Allmaras, that finds t1p by searching for V1MAX and DMIN but that starts the search from the time of D1MAX; and that, failing to find V1MAX and D1MAX assigns values as explained below. Or, the user can choose method M2 that finds D1MAX and fits a line tangent to the first rising limb and a horizontal line tangent to the baseline before the first rising limb and solves the intersection for t1.bis. Method M2 then adds a user set time, t_C, to t1.bis to get t1. The time t_C = t1 - t1.bis is found by measurements on probes installed in wet soil using method M1.

7.6.5 Finding Travel Times

Times t1 and t2 are reliably found by a combination of searches and decisions based on the results of those searches. In this discussion the wave form is assumed to consist of NP digitized data pairs of voltage and time with equal increments of time between consecutive data pairs.

1. Smooth data and first derivative using the Savitsky-Golay method and user set number of points, and find the maximum and minimum first derivative, maxDeriv and minDeriv.

2. Scan the wave form data from D2Lim to EndPt to find the lowest value, VMIN, and corresponding time, t2.1.

3. Scan the first derivative in a loop from StartPt to D1Lim to find the first maximum value, D1MAX, and associated time tD1MAX. If tD1MAX is greater than t2.1 then reduce D1Lim by NP/40 and try again. If D1Lim reaches 0 then write zeros to output.

4. Scan wave form data from tD1MAX+30 to EndPt for the lowest value, VMIN, and associated time, t2.1.

5. Scan wave form data from tD1MAX to tD1MAX + NP/8 to find the highest value, V1MAX, and associated time, t1p. Update V1MAX whenever the wave form value is higher than V1MAX and accumulate a count whenever the wave form value is lower. If count is greater than t1Swath then stop the search. This avoids finding the second peak if double peaks exist. If the wave form is continuously rising then t1p may be greater than tD1MAX + NP/20. If so then set t1p equal to tD1MAX + NP/20 and set V1MAX to the wave form value at that time.

6. Unless the global minimum method for finding t2 is forced, scan the derivative data from D2Lim to EndPt for the maximum derivative, D2MAX, and corresponding time, t2.2.

7. If the t2 derivative peak method is forced or if the t2 method is automatic and D2MAX is larger than D2Thresh then scan the data from t2.2 to t2.1 to find the zero derivative nearest to t2.2. Redefine t2.1 at this point and take the value of the wave form at this point as VMIN. If no zero derivative is found in this range of data then set t2.1 equal to t1p plus tatVMINFrac times the quantity (t2.2 - t1p) and set VMIN equal to the corresponding value of the wave form.

8. If the method for t2 is automatic and D2MAX is less than D2Thresh then set t2.2 equal to t2.1 plus the offset (RiseLimbOffset) specified by the user and set D2MAX equal to the corresponding value of the first derivative. Then set t2.1 equal to t1p plus tatVMINFrac times the quantity (t2.2 - t1p) and set VMIN equal to the corresponding value of the wave form.

9. If the local minimum method for t2 is forced then set t2.2 to t2.1 plus RiseLimbOffset (limited to less than or equal to NP) and set D2MAX to the corresponding value of the first derivative.

10. Regardless of how t2.2 is determined set Vt2.2 equal to the wave form value at t2.2.

11. Fit by linear regression a line to the base line between t2.1 and t2.1-BaseSwathWidth where BaseSwathWidth is a user chosen number of data points. If the slope of this line is positive then force a regression fit to the base line rather than a horizontal line tangent to VMIN.

12. Scan the derivative data from t1p to t1p plus t1Swath to find the lowest derivative value, DMIN, and corresponding time, tDMIN, which are associated with the descending limb of the first peak.

13. If DMIN is greater than -0.01 then set DMIN=(yll-yuu)/(xuu-xll), and set tDMIN equal to t1p + 1. The

values of yll and yuu are the minimum and maximum of the wave form, respectively, and the values of xll and xuu are the minimum and maximum of the x-axis. Thus, the slope is scaled to the wave form amplitude.

14. Set VtDMIN equal to the wave form value at tDMIN, and if this value is greater than V1MAX then set VtDMIN to V1MAX.

15. Calculate the time of the intersection of tangent lines for t1 and if this time is less than t1p then increase the value of tDMIN and the magnitude of the slope, DMIN, until the intersection is at t1p or greater.

16. If t1 is less than the safety limit, SafetyLim, then write zeros to the file.

17. Set up limits on data used to fit tangent line to second rising limb as t2.2-Xinc and t2.2+Xinc where Xinc is user chosen. If these limits are out of range then write zeros to file.

19. If actual point to point slope near tD1MAX is greater than smoothed slope, D1MAX, then set D1MAX to actual maximum slope.

20. Examine derivative before first rising limb for slope close to zero (slope lesser in magnitude than [maxDeriv-minDeriv]/100). If such points are found then use the average wave form value for those points as the intercept for a line tangent to the baseline with slope of zero. If such points are not found then set the intercept of the horizontal line to the minimum wave form value to the left of tD1MAX.

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Appendix 7-A.

```
SUB BestDistDv.Vp (ProbeLen, FtMtrs, Theta)
'Routine for choosing the best combination of Dist/Div and Vp for a given
'probe length based on inversion of Topp's equation for permittivity, Ka,
'as a function of water content.  Written in Microsoft BASIC 7.1 by Steven R.
Evett

'ProbeLen is probe length in meters.
'FtMtrs 'If 1 then units are feet else units are m.
'Theta is volumetric water content (m^3/m^3).

SHARED Vp
SHARED Dist
SHARED DistDv
SHARED CardType%

i% = 10
DIM TimeErr(i%)
DIM DistVal(i%)

'Limit values of water content:
IF Theta < 0 THEN Theta = 0
IF Theta > .6 THEN Theta = .6

'Calculate the apparent permittivity (Ka) (Topp et al., 1980):
Ka = 3.03 + 9.3 * Theta + 146! * Theta * Theta - 76.7 * Theta * Theta * Theta

'The velocity of propogation is a function of Ka:
v = .299792 * 1E+09 / SQR(Ka)

'The travel time is a function of v and probe length:
tt = ProbeLen / v

'Assume that the travel time should occupy 70% of the screen max.
NewTtFull = (tt / .7) * 1E+09   'in ns

row% = CSRLIN
col% = POS(0)

TryAgain% = 0
SELECT CASE CardType%
CASE 5
Start.Search:
    'Try smallest Dist first, then next biggest, etc.
    'Get Dist for i=1 to 10:
    FOR i% = 0 TO 10
       DistDv = i%
       ReturnDistDv 'This returns one of the 11 possible Dist/Div settings.
       'Make sure DistM is in meters:  DistM is the distance per division.
       IF FtMtrs = 1 THEN
           'was in feet, convert to meters
           DistM = Dist * .3048
       ELSE
           'was in meters
           DistM = Dist
       END IF
       'Try biggest Vp first, then go to smallest
       FOR Vp = .99 TO .39 STEP -.01
           TtFull = DistM * 10 / (Vp * .2997925)
           IF TtFull >= NewTtFull THEN EXIT FOR
       NEXT Vp
```

```
        IF TtFull >= NewTtFull THEN EXIT FOR
     NEXT i%
     TimeError = (TtFull - NewTtFull) / NewTtFull
     BestDist = Dist
     IF ABS(TimeError) > .02 THEN
         PRINT "Best DIST/DIV and Vp not found."
         PRINT "Error was"; TimeError * 100; "%"
         PressAKey (5)  'Wait for a key press before continuing.
     END IF
     'One combination of Vp and Dist/Div is known.
     'The Dist/Div value is in BestDist.  Print both Vp and Dist/Div:
     PRINT "        For VWC ="; Theta;
     LOCATE row% + 1, col%
     PRINT USING "recommend Vp: .## "; Vp;
     PRINT "and DIST/DIV:"; BestDist;
     IF FtMtrs = 1 THEN
         PRINT "ft";
     ELSE
         PRINT "m";
     END IF

CASE ELSE
'For Tektronix 1502 cable tester, not 1502B/C.
'Provide two closest Dist/Div values for given Vp.
Start.Search2:
     'Get Dist for i=1 to 10:
     FOR i% = 0 TO 10
        DistDv = i%
        ReturnDistDv
        'Make sure DistM is in meters:
        IF FtMtrs = 1 THEN
            'feet
            DistM = Dist * .3048
        ELSE
            'meters
            DistM = Dist
        END IF
        'Use actual Vp first, and return error if TimeErr is too great
        TtFull = DistM * 10 / (Vp * .2997925)
        TimeErr(i% + 1) = (TtFull - NewTtFull) / NewTtFull
        DistVal(i% + 1) = Dist
        IF TimeErr(i% + 1) > 0 THEN EXIT FOR
     NEXT i%

     LOCATE 22, col%
     PRINT "For VWC ="; Theta;
     PRINT USING " and for Vp: .## "; Vp;
     FOR j% = i% TO i% + 1
         LOCATE 22 + 1 + j% - i%, col%
         PRINT "could use DIST/DIV:"; DistVal(j%);
         IF FtMtrs = 1 THEN
             PRINT "ft";
         ELSE
             PRINT "m";
         END IF
         PRINT USING ". Error: ###"; TimeErr(j%) * 100;
         PRINT "%";
     NEXT j%
END SELECT
REDIM TimeErr(0)
REDIM DistVal(0)
END SUB
```